ADAPTIVE WAVEFORM CORRELATION DETECTORS FOR ARRAYS: ALGORITHMS FOR AUTONOMOUS CALIBRATION

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ABSTRACT

Waveform correlation detectors compare a signal template with successive windows of a continuous data stream and report a detection when the correlation coefficient (CC), or some comparable detection statistic, exceeds a given threshold. Since these methods exploit characteristic details of the full waveform, they provide exquisitely sensitive detectors with far lower detection thresholds than typical STA/LTA algorithms. The drawback is that the form of the sought after signal needs to be known quite accurately a priori which limits such methods to instances of seismicity whereby a very similar signal has already been observed by every station used. Such instances include earthquake swarms, aftershock sequences, repeating industrial seismicity, and many other forms of controlled explosions. The reduction in the detection threshold is even greater when the techniques are applied to multiple channels since stacking can be performed on the correlation coefficient traces with a significant array-gain. A detected event that is co-located with the master event will record the same time-difference at every site in an arbitrarily spaced network which means that the correlation coefficient traces can be stacked coherently even when there is little or no similarity between the actual signals at the different sites.

The focus in the first year of the contract was testing limits of detection capability for almost co-located seismic events. It was demonstrated that the signal from a magnitude 3.5 earthquake could be used as a template to detect nearby events 3 orders of magnitude smaller using multi-channel correlation detectors. This is an improvement better than one magnitude unit for an ARCES-style regional seismic array and better than 1.5 magnitude units for a larger network where coherent array processing was not possible. In the second year, situations were considered where waveforms from closely spaced seismic events differed significantly, primarily due to complicated source-time functions. It was demonstrated that array-based waveform correlation could still be applied effectively by considering the CC trace alignment over the network, maintaining a low detection threshold and low false alarm rate. The application of correlation methods to expose and account for incorrect instrumental timing has been studied throughout.

In this third and final year of the contract, we have examined the size of the "correlation footprint" —how far apart two seismic events may be located and still be detected by correlation using a waveform template. Correlating high-frequency regional signals between sensors of regional arrays suggests through reciprocity that the single channel correlation distance is of the order of only a few hundred meters, and this is confirmed using sensors of the ARCES array for superbly constrained events in a Barents Sea seismic profile. Applying the full array increases the correlation distance to several kilometers, the array-gain resulting from the close alignment of the CC traces. Even a footprint of this size is still far too small for such correlation methods to classify extensive aftershock sequences effectively. We use aftershocks of a magnitude 6 earthquake near Svalbard to demonstrate the inadequacy of individual aftershocks as master events for the full aftershock sequence. No matched filter, constructed from waveforms of any individual aftershock, detected more than a small subset of the sequence. Incoherent correlation detectors can be constructed using multiple waveform envelopes from different seismogram transformations (e.g., different frequency bands, 3-C rotations, and beams) together with characteristic traces such as semblance and F-statistic for specified alignments. The incoherent detectors were demonstrated to be highly effective at identifying events that were clearly closely related to the mainshock, albeit undetected using a basic matched filter. The incoherent detectors are used to identify new master events and generate new waveform templates, and the classical correlation detectors are used to push down the detection threshold within the emergent clusters.

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OBJECTIVE

The overall objective of this three-year study is to develop and test a new advanced, automatic approach to seismic detection using waveform correlation, with special application to seismic arrays. The principal goal is to develop an adaptive processing algorithm. By this we mean that the detector is initiated using a basic set of reference ("master") events to be used in the correlation process, and then an automatic algorithm is applied successively to provide improved performance by extending the set of master events selectively and strategically. These additional master events are generated by an independent, conventional detection system. A periodic analyst review will then be applied to verify the performance and, if necessary, adjust and consolidate the master event set.

RESEARCH ACCOMPLISHED

In the first year of this project, the primary focus was upon quantifying the improvement in detection capability provided by full-waveform correlation detectors. Inspired by the detection of very weak chemical explosions using the signals of stronger co-located events as templates (Stevens et al., 2006), Gibbons and Ringdal (2006) estimated (by sinking a template signal into increasing levels of background noise) that an improvement of approximately one order of magnitude was possible, with an even greater improvement afforded by the use of arrays. This result was confirmed for an actual example of natural seismicity at regional distances (Ringdal et al., 2006, Gibbons et al., 2007a) where the correlation detections made could be confirmed using data from a local seismic network. The signal from a magnitude 3.5 earthquake was used as a template to detect co-located events, using only array stations at distances of over 600 km from the epicenter. With a very low false alarm rate, earthquakes of magnitudes as small as 0.5 were detected using this system. It was pointed out that the improvement in detectability at a small aperture regional array was approximately 1.0 magnitude units, whereas the improvement at an equidistant array with very poor inter-site coherence was even greater: approximately 1.5 units. Traditional array processing methods fail with incoherent large aperture arrays, whereas the correlation detectors are equally effective over arbitrary network geometries.

In the second year, situations were considered in which waveforms from subsequent almost co-located events differed significantly (primarily due to variations in the source-time histories of the events). It was demonstrated (Ringdal et al., 2007) that multi-channel waveform correlation detectors were nevertheless able to classify such a sequence very effectively, provided that the alignment of the cross-correlation traces was consistent with the occurrence of co-located events. In this case, it was never sufficient only to detect individual local correlation maxima from a single channel correlation trace.

A consequence of the necessary alignment of the cross-correlation traces at all stations is that incorrect timing at one station or more should usually be detectable. Gibbons (2006) demonstrated how the detection of almost repeating mining-induced seismic events could be exploited to measure accurately a timing disparity on a distant single 3-component station. The principles involved are similar to those employed by Rubin (2002) who measured timing disparities from inconsistencies in high-precision earthquake catalogs, although the method employed here requires only waveform similarity without necessarily any knowledge of the source location.

This paper summarizes the principal activities in the third and final year. Firstly we explore the extent of the "correlation footprint;" first using an argument based around reciprocity, and then using recordings at an array station of multiple events in a seismic profile. Secondly, we consider a case study where a large earthquake is followed by an extensive aftershock sequence. It was immediately evident that the waveforms from the main event did not constitute an effective matched filter detector for aftershocks. We explore the possibility of an incoherent type of correlation detector which is able to associate potential master signal templates from the sequence such that the pool of waveform templates can be expanded strategically in order to detect and categorize a maximum number of the seismic events.

Investigating the Size of the Correlation Footprint

When assessing the applicability of waveform correlation detectors, it is of paramount importance to be able to estimate how far from the master event a subsequent event can be such that it can still be detected using the available signal template. We use the term "correlation footprint" to describe the region surrounding the master event location in which seismic events can be detected using this template. It is important to note that we are assuming the "best case scenario" for detectability, i.e. that the events have similar source mechanisms and similar source-time functions. Two seismic events which are essentially co-located may not correlate if these properties differ significantly.

The coherency of seismic signals over receiver arrays has been studied at great lengths since the signal semblance at various inter-site distances dictates how useful a given design of seismic array will be for detecting and estimating different classes of seismic signals. For example, a teleseismic signal dominated by low frequency energy can be highly coherent over a network with an aperture of many tens of kilometers, whereas higher frequency signals can be quite incoherent if the instruments are separated by more than a few hundred meters. Similar arguments are likely to apply to the source region and the size of the correlation footprint is likely also to be a function of the dominant frequency of the signal. Geller and Mueller (1980) suggest that well-correlating events are likely to be separated by no more than a quarter wavelength at the dominant wavelength. To examine the extent of the correlation footprint as a function of frequency band and signal duration, we would ideally have records of many hundreds of seismic events with precisely known locations over a very wide range of inter-event distances. The locations of earthquakes are seldom sufficiently well known, and it is expensive and logistically difficult to produce an event array of explosions from which a sufficient number of observations can be made. Mining explosions are often suitable for such studies (Harris, 1991) although these events are often associated with very differing and complicated source-time functions.

It can be informative to consider the reciprocal case, where the signal from a single event is recorded on closely spaced instruments of an array (an approach also taken by, for example, Menke, 1999). Figure 1 shows the signal recorded at the central element (ARA0) of the ARCES array from a surface explosion at a site in Finland at a distance of approximately 178 km (details of these events are provided by Gibbons et al., 2007b). At the sites in the A-ring (see Figure 1), with inter-site distances on the order of 150 m, a clear correlation peak indicates that the signals at these sites can easily be detected by a matched filter using the ARA0 signal as the template. Under our supposition of reciprocity, we assume that the signal from an event 150 m from the master event could probably be detected using this signal template. Figure 1 shows that the signal at the ARB1 site (a distance of 350 m) is also detected clearly using the ARA0 template, albeit with a lower value of the correlation coefficient, whereas the signals at the outer-ring sites (distances over 500 m), are too dissimilar for a matched filter detection. Similar calculations were repeated using the signals from all of the other elements as templates, and therefore covering a very large range of inter-site distances. For this regional event, with a 60-second-long template filtered from 2 to 8 Hz, the signal at a site at ARCES can be detected by correlation using the signal from a different site, provided the inter-site distance is less than about 500 m. This is consistent with the quarter wavelength argument of Geller and Mueller (1980).

In August 2007, a series of marine seismic profiles was shot in the Barents Sea under the name PETROBAR. One of these profiles is displayed in Figure 2 and was of great interest because most of the shots were reasonably well recorded by the ARCES array at a distance of less than 250 km. Unusually for such marine profiles, there are clear S-phases detected at the array. The signals are best observed in the 4-8 Hz frequency band and waveforms filtered in this range are displayed for a segment of a little over 26 minutes in Figure 3. The distance between the events is approximately 200 m, with an approximate 90-second delay between each shot. For the distance between the profile and ARCES, this allows a 60-second template to be extracted for each event, containing both P- and S-phases and coda, which is not contaminated with the signal from any other shots. Figure 3 also displays the single-channel cross-correlation traces calculated from the template as indicated. There is some variation between the different ARCES channels, but the primary observation is that, with only a single channel, the signal from one event can be used as a template to detect events up to 600 m away. This is consistent with the results from the reciprocity experiment described above. This calculation was repeated using every single event as a master event and the pattern remained largely unchanged. Although signals with an exceptionally low signal-to-noise ratio (SNR) usually resulted in a poorer detection capability, there was no obvious connection between the SNR of the master event signal and how many adjacent shots could be detected using the matched filter detector (Shelly et al., 2007, describe a correlation detection case study whereby the master event signals almost inevitably suffer from a low SNR).
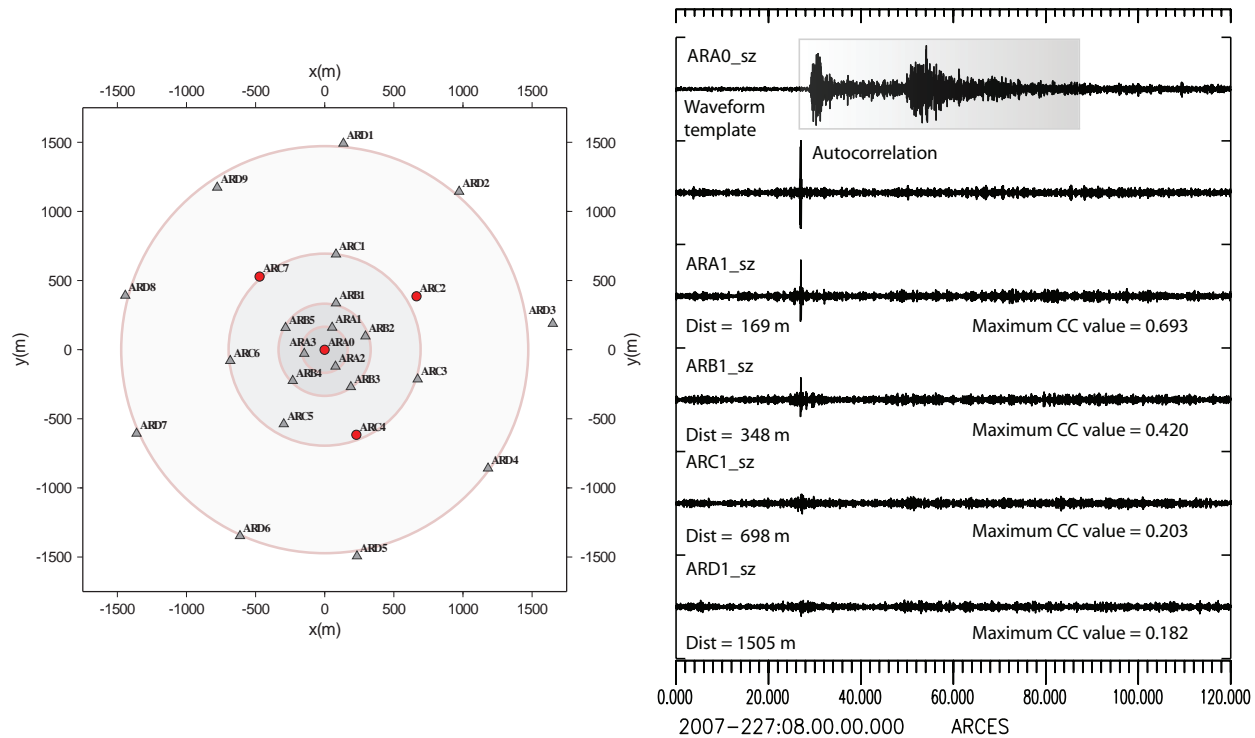
Figure 1. (Left) Geometry of the ARCES seismic array. (Right) An attempt to detect, using single-channel waveform correlation, the seismic signal from a given event on various vertical sensors of the ARCES array using the signal recorded at the central ARA0 site as the waveform template. The length of the template is 60.0 seconds and all waveforms are filtered 2.0–8.0 Hz.

The most important observation is that when the cross-correlation traces are stacked, the signals from events at several kilometers distance are detected from the given template. This result is non-intuitive and provides considerable motivation for the use of array-based waveform correlation detectors as opposed to detectors using only single stations. The preliminary investigations of Gibbons and Ringdal (2006) and Gibbons et al. (2007a) went only as far as to suggest that correlation trace stacking should improve the detectability of a co-located event with a lower SNR. That network stacking should increase the size of the correlation footprint is, however, consistent with an observation of Harris (1991) that statistically significant correlation coefficients were obtained between events at greater distances when a full-array was used than when only a single channel was used. Harris (1991) suggests that the quarter-length scale correlation footprint of Geller and Mueller (1980) could be replaced with a two-wavelength footprint.
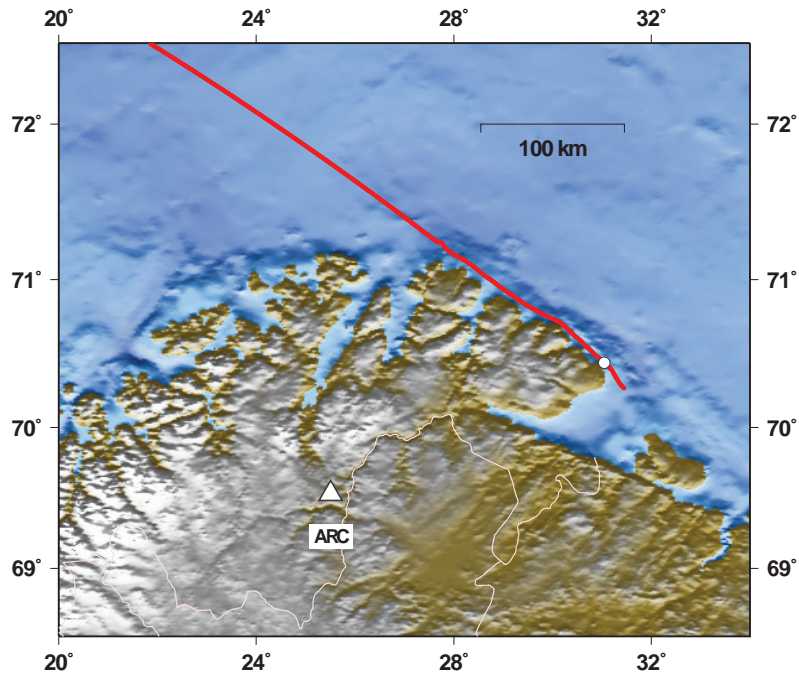
Figure 2. Locations of shots in the PETROBAR 1 marine seismic profile in relation to the ARCES regional seismic array. The white circle shows the location of shot 121 with coordinates 70.444386°N, 31.053447°E and origin time 2007-221:03.02.32.523. For this part of the profile, shots are separated by approximately 200 m.
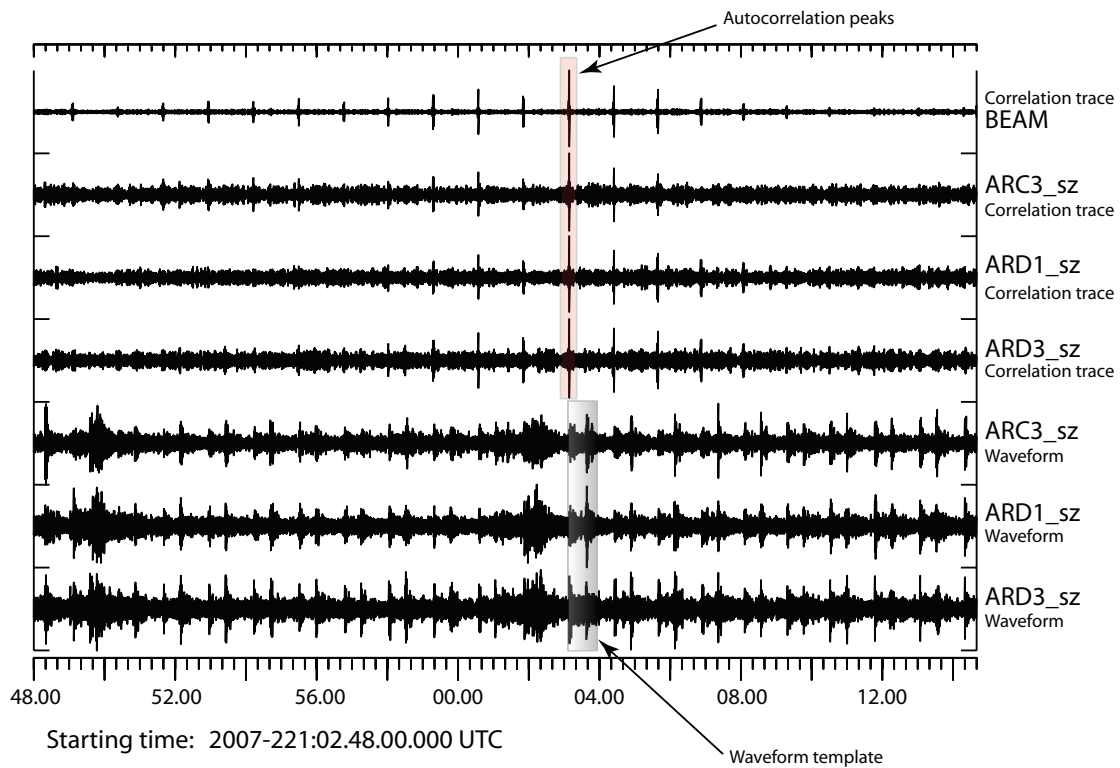

Figure 3. Waveforms and cross-correlation traces with a template from the shot 121 signal.

Algorithms for Autonomous Calibration

The classification of extensive aftershock sequences from large earthquakes is one of the most challenging problems faced by data centers engaged in the monitoring of nuclear explosions. The shear number of events requiring manual analysis and relocation can lead to significant backlogs in the compilation of event bulletins and the subsequent screening of unambiguous earthquakes. The identification and association of aftershocks should ideally be performed with as high a degree of automation as possible such that limited analyst resources are only necessary to provide checks on the results of the automatic processing.

On February 21, 2008, a magnitude 6 earthquake occurred in the Storfjorden region close to Svalbard. Whilst not large in a global perspective, this event illustrates beautifully the difficult task of aftershock identification. The aftershock sequence consisted of many hundreds of events within the first two days and a very much increased level of seismicity for several months afterwards. The simulated helicorder plot from the SPITS array (Figure 4, left) illustrates the largest events for February 23, 2008. The dynamic range at the SPITS array (Figure 4, right) saturated under the main event and the data is clipped on all channels. The signal at the ARCES array was not clipped and a template was extracted rapidly in an attempt to detect aftershocks using a correlation detector. It became evident that very few of the numerous aftershocks were being detected using this template, with essentially no convincing detections. Following the analyst review of the aftershocks in the first few days following the main event, matched filter detectors were initiated for a large number of master events. Many of these detectors were successful in detecting large numbers of other events and it became clear that a cluster analysis of the sequence would be possible using associations indicated by high values of the correlation coefficient.
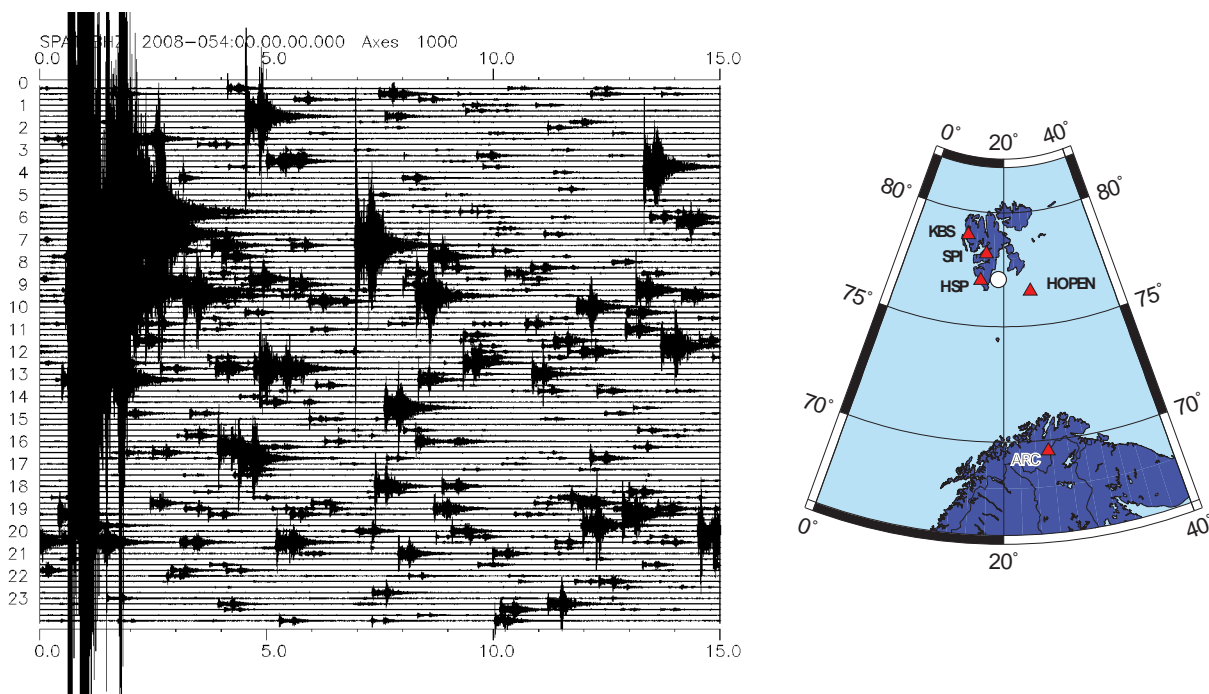

Figure 4. (**Right**) **Location of the M=6 Storfjorden, Svalbard, earthquake February 21, 2008 (white circle), in relation to the International Monitoring System arrays ARCES and SPITS and the 3-component stations KBS, HSP, and HOPEN. (Left) Simulated helicorder plot for February 23, 2008, filtered 2-8 Hz, on the SPA1_BHZ instrument of the SPITS array. Essentially all of the signals visible on this plot are aftershocks from this event.**

In performing this correlation analysis, we have, however, been completely dependent upon a bulletin of manually located events; our goal is to classify the sequence automatically. The preliminary automatic event bulletin (GBF: Ringdal and Kværna, 1989) upon which the reviewed bulletin is based is not accurate enough for an unambiguous association of events; errors in origin time and hypocentral location are too large even for the setting of time-windows for waveform correlation analysis. The fixed-window template method of Gibbons et al. (2005) is also not applicable.

This algorithm is designed for very small source regions (maximum length-scale of 2 or 3 km) for which numerous events have already been observed for the calibration of processing parameters. A preliminary examination of event location estimates for the Svalbard sequence indicates a source region aperture at least an order of magnitude larger than this. In addition, we would like to assume that our main shock has occurred in a location where no event has been observed previously, meaning that no calibration data are available.
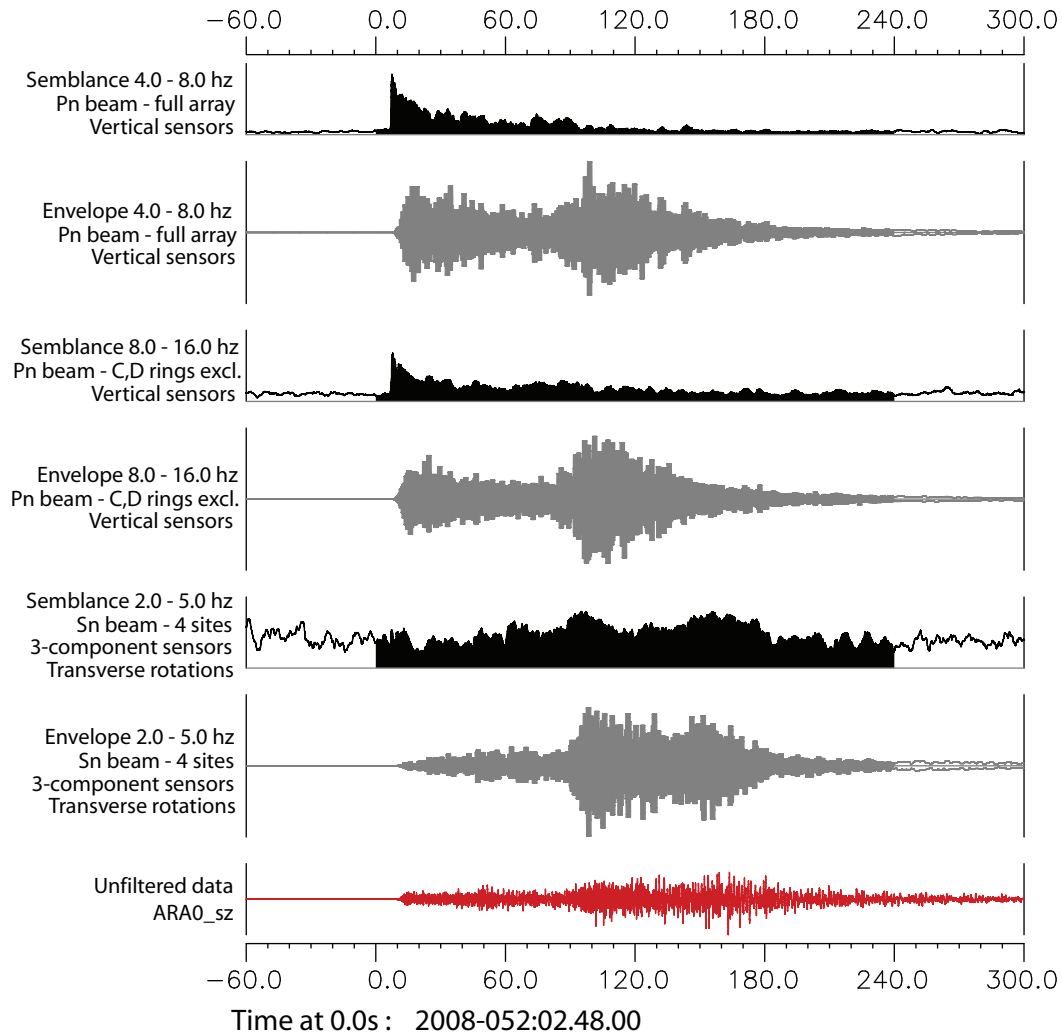

Figure 5. Construction of an "incoherent matched filter detector" from ARCES waveforms from the February 21, 2008, Storfjorden main event. The small aperture of the ARCES array means that the variability of waveform envelopes between sensors is minimal and that there would therefore be very little advantage in stacking of correlation coefficient traces. However, the coherence of the waveforms can be exploited to form beams using time-delays corresponding to the slownesses of the various observed seismic phases. This emphasizes different sections of the seismograms at times characteristic of the source-receiver distance, although with far less sensitivity than that necessary for setting of the time-windows for f-k analysis prescribed in the algorithm of Gibbons et al. (2005). In addition to the envelopes of beams formed for different slowness vectors, different component rotations, and different frequency bands, we have the corresponding characteristic functions (semblance and the related F-statistic) that can also be correlated against the same functions evaluated for the incoming data stream. The semblance functions are greatest for the initial Pn-arrivals on the corresponding beams. The semblance function for the Sn beam on the transverse components suffers from the reduced number of instruments and non-optimal coherence of the Sn phase between these four widely spaced sensors.

An alternative possibility is that of correlating characteristic functions of the waveforms against the corresponding transformations of the incoming data. Since we do not have "ripple for ripple" correspondence between the events we wish to associate, we need to correlate some "coarser" signature of the generated signals. Viable automatic detection and location schemes have been constructed that correlate waveform envelopes (see, for example, Withers et al., 1999) but we need to proceed with caution since the small aperture of our regional seismic array means that the waveform envelopes on the different channels show essentially the same features at the same times. The standard waveform correlation detector (a "coherent correlation detector") exploits details in the full wavetrain that are specific to the given site. For this reason, one would rarely apply beamforming prior to correlation since this would lose much of the available information about the signal's signature at each site - beamforming is applied after the correlation to much greater effect. However, since we wish to compare waveform envelopes, or some other signal attributes, (i.e. an "incoherent correlation detector") we should apply every possible transformation to the waveforms from a given event that are likely to result in a shape specific to that source region. The construction of part of the "incoherent template" at ARCES for the Svalbard event is displayed in Figure 5.
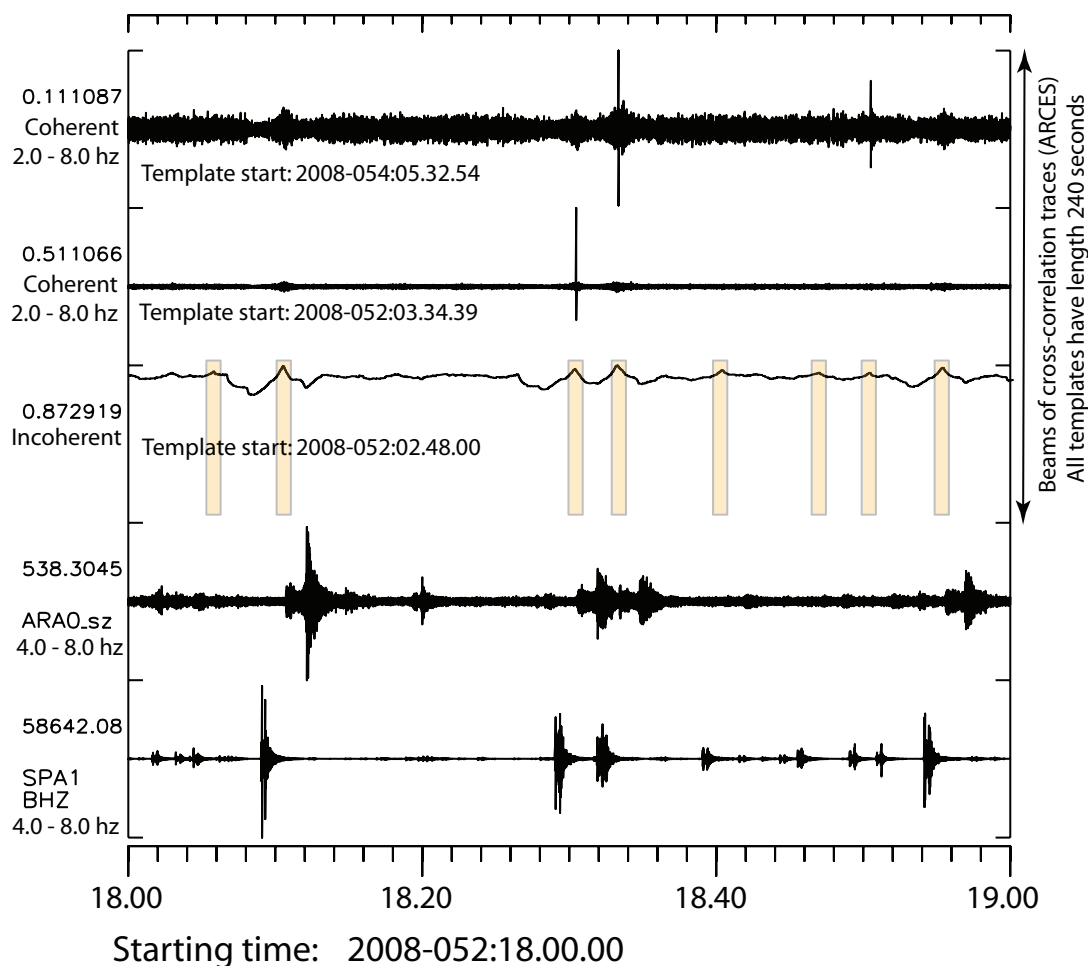

Figure 6. Detections of aftershocks using the incoherent template illustrated in Figure 5 and using two standard correlation detectors. The template for the top trace detects two events during this one-hour interval, the template for the second trace detects one (different) event, and the incoherent template takes all three events plus 5 additional events. Data from the SPITS array in the lowermost trace confirms that each of the incoherent correlation detections does indeed correspond to a Svalbard aftershock. Note that the signals at the SPITS array arrive approximately 90 seconds prior to the ARCES detections due to the travel-time differences. The Svalbard aftershocks visible in the data that are not detected by the incoherent correlator occur within close succession of other Svalbard events, and such rapid sequences cannot be resolved using the four-minute templates at ARCES.

Unlike the standard correlation detections, the peaks on the incoherent correlation trace beam are somewhat marginal (Figure 6) but, with a threshold carefully and empirically set, the detector has been demonstrated to identify essentially all of the major events in this sequence and with a very low false alarm rate.

The relationship between the three uppermost traces in Figure 6 suggests a system for the semi-autonomous readjustment of a waveform template pool for new master events. Signals from such events could be selected either for standard correlation detectors or, alternatively, as new templates to add to the basis for a signal subspace detector (Harris, 1989). A candidate template is any event that triggers a detection on the incoherent detector (probably verified by an analyst before accepting). The time of the corresponding event is searched for in the lists of correlation detections from the existing correlation detector pool. If an entry is found with a sufficiently high correlation coefficient, we can most likely ignore the new event since it seems that we already have a template that is likely to detect subsequent occurrences of this signal. If no entry in existing detection lists is found, or if there are detections that are marginal, it is probably sensible to include the new event as a waveform template in order to detect further occurrences of this signal, including those which are too weak for the incoherent method to detect.

CONCLUSIONS AND RECOMMENDATIONS

Two major topics have been investigated in the third and final year of this contract.

Firstly, it has been demonstrated that the Geller and Mueller quarter wavelength argument is probably reasonable for the size of the correlation footprint for single channel matched filter detectors. Stacking the correlation coefficient traces over an array or network results not only in an improvement in detectability for weaker co-located events, but also an expansion of the size of the correlation footprint. For the regional signals in the PETROBAR-1 profile displayed here, the correlation distance for a single channel was of the order 500–600 m. When the full ARCES array was employed, this distance was increased to several kilometers.

Secondly, an extensive aftershock sequence has been studied whereby the signal from the main event did not constitute a suitable template for the detection of subsequent seismic events. Using various transformations of the signal from the main event (e.g., beamforming, filtering, rotation) we can construct a template of characteristic functions for the extended source region that constitutes an "incoherent correlation detector". This detector successfully identified large numbers of the aftershocks with a very low false alarm rate. It is likely that the simultaneous running of an incoherent detector together with numerous standard correlation detectors will allow a more complete characterization of the aftershock sequence than would be possible if only the traditional matched filter detectors were to be used.

ACKNOWLEDGEMENTS

REFERENCES

Geller, R. J. and Mueller, C. S. (1980). Four Similar Earthquakes in Central California, in *Geophys. Res. Lett*. 7: 821–824.

Gibbons, S. J. (2006). On the Identification and Documentation of Timing Errors: An Example at the KBS station, Spitsbergen, *Seism. Res. Lett*. 77: 559–571.

Gibbons, S. J., Bøttger Sørensen, M., Harris, D. B. and Ringdal, F. (2007a). The detection and location of low magnitude earthquakes in northern Norway using multichannel waveform correlation at regional distances, in *Phys. Earth Planet. Int*. 160: 285–309.

Gibbons, S. J., Kværna, T., and Ringdal, F. (2005). Monitoring of seismic events from a specific source region using a single regional array: A case study, in *J. Seismol.* 9: 277–294.

Gibbons, S. J. and Ringdal, F. (2006). The detection of low magnitude seismic events using array-based waveform correlation, in *Geophys. J. Int*. 165: 149–166.

Gibbons, S. J., Ringdal, F., and Kværna, T. (2007b). Joint seismic-infrasonic processing of recordings from a repeating source of atmospheric explosions, in *J. Acoust. Soc. Am.* 122: EL158–EL164.

Harris, D.B. (1989). Characterizing Source Regions with Signal Subspace Methods: Theory and Computational Methods, Lawrence Livermore National Laboratory report number UCID-21848.

Harris, D.B. (1991). A waveform correlation method for identifying quarry explosions, in *Bull. Seism. Soc. Am.* 81: 2395–2418.

Menke, W. (1999), Using waveform similarity to constrain earthquake locations, in *Bull. Seism. Soc. Am.* 89: 1143–1146.

Ringdal, F. and Kværna, T. (1989). A multi-channel processing approach to real time network detection, phase association, and threshold monitoring, in *Bull. Seism. Soc. Am.* 79: 1927–1940.

Ringdal, F., Gibbons, S. J. and Harris, D. B. (2006). Adaptive waveform correlation detectors for arrays: algorithms for autonomous calibration, in *Proceedings of the 28th Seismic Research Review*, *Ground-based Nuclear Explosion Monitoring Technologies*, LA-UR-06-5471, Vol. 1, pp 444–454.

Ringdal, F., Gibbons, S. J. and Harris, D. B. (2007). Adaptive waveform correlation detectors for arrays: algorithms for autonomous calibration, in *Proceedings of the 29th Monitoring Research Review: Ground-based Nuclear Explosion Monitoring Technologies*, LA-UR-07-5631, Vol. 1, pp 444–453.

Rubin, A. M. (2002). Using Repeating Earthquakes to Correct High-Precision Earthquake Catalogs for Time-Dependent Station Delays, in *Bull. Seism. Soc. Am.* 92: 1647–1659.

Shelly, D. R., Beroza, G. C., and Ide, S. (2007). Non-volcanic tremor and low-frequency earthquake swarms. *Nature* 446: 305–307.

Stevens, J. L., Gibbons, S., Rimer, N., Xu, H., Lindholm, C., Ringdal, F., Kværna, T., Murphy, J. R. (2006). Analysis and simulation of chemical explosions in nonspherical cavities in granite, in *J. Geophys. Res.* 111: B04306, doi:10.1029/2005JB003768.

Wessel, P. and Smith, W. H. F. (1995). New version of the generic mapping tools, *EOS Trans., Am. geophys. Un.* 76: 329.

Withers, M., Aster, R., and Young, C. (1999) An automated local and regional seismic event detection and location system using waveform correlation, in *Bull. Seism. Soc. Am.* 89: 657–669.